RFQ and LEBT Progress

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Summary

LBNL is tasked with the design of RFQs for both FNAL (PXIE) and IMP (Lanzhou)

These two CW RFQs are very similar

The beam dynamics and structure design have been converging to nearly a single design, differing only in details of beam parameters.

The mechanical design is compatible with available manufacturing techniques in both China and the USA, such as avoiding e-beam welding, and using brazing only, (except on the ends of the water passages.)

Both projects are on an accelerated schedule

The beam dynamics design for PXIE is complete

The mechanical design is based on RFQs previously manufactured or subjected to extensive engineering analysis at LBNL, and the engineering concept is complete.

RFQ Parameter List

	PXIE	IMP	
Input energy	30	35	keV
Output energy	2.1	2.1	MeV
Frequency	162.5	162.5	MHz
DC Current	5-15	5-20	mA
Vane-vane voltage	60	65	kV
Length	440.4	416.2	cm
RF Power	100	110	kW
Duty Factor	100	100	percent

Recent RFQ Design Changes

New beam dynamics design, PXIE now very similar to IMP design
99.7% capture

Transmission, emittance parameters hold well to over 10 mA

Slightly shorter: 440.2 cm, down from 448 cm

Slightly higher vane voltage: 60 kV, up from 58 kV

Change radial matcher to Kolomiets design: easier to cut, and
less correction needed to maintain flat field along RFQ

Power requirement up 5%, but still less than 100 kW for
60% of theoretical Superfish Q_0

Highlights of Modified Design

Constant cross-section of structure along entire length
constant transverse vane radius: only one form cutter profile needed

The minimum longitudinal vanetip radius = 1.03 cm: easy design of cutter

Four modules, joined with butt joints

Each module assembled with brazes: no electron-beam welding, except to close the ends of the gun-bored water channels.

No complex brazing operations: (No Glidcop in structure)

Wall power density less than 0.7 Watts/cm^2 CW (SNS was 1.7 at 6% duty factor)

Pi-mode stabilizers offer very large mode separation and field stability against machining errors.   32 stabilizers used: 4 pairs/module.

Mode separation, quadrupole to dipole is 13.5 MHz.

Length only 2.4 free-space wavelengths long (SNS was over 5 wavelengths)

80 tuners, 48 sensing loops, two drive ports

Beam Dynamics Simulations

Beam load derived from ion source emittance measurements: halo present
Capture is 99.76% of 5 mA input beam

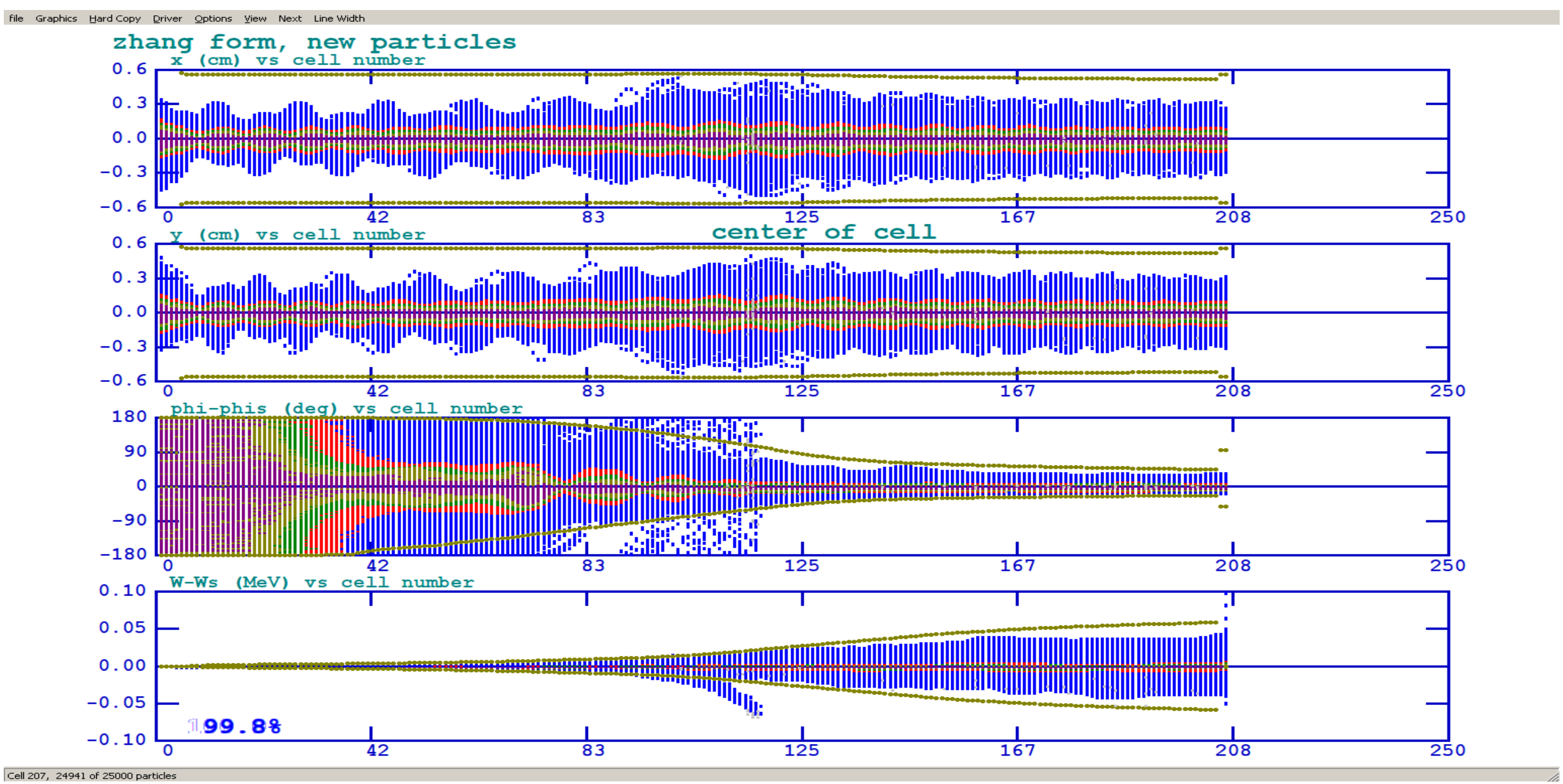
Transverse output emittance 0.15 pi mm-mr
Longitudinal emittance 0.64 keV-nsec

Ellipse parameters at cell 207:

	alpha	beta	Emit,u,rms	Emit,n,rms
		cm/rad	cm-mrad	cm-mrad
x:	-1.1660	15.4066	0.2242	0.01508
y:	1.4086	19.3708	0.2265	0.01523
		deg/MeV	MeV-deg	MeV-deg
z:	0.0456	1002.8577	0.0389	0.03887

Percent of beam within rms multiples for each phase plane:

	1rms	2rms	3rms	4rms	5rms	6rms	7rms	8rms	9rms	10rms
x:	42.5	67.4	80.8	87.5	91.4	93.9	95.4	96.7	97.5	98.2
y:	41.9	66.8	80.7	87.8	91.5	93.9	95.6	96.8	97.5	98.1
z:	46.8	70.7	83.5	88.7	91.4	93.4	95.0	96.2	96.9	97.5

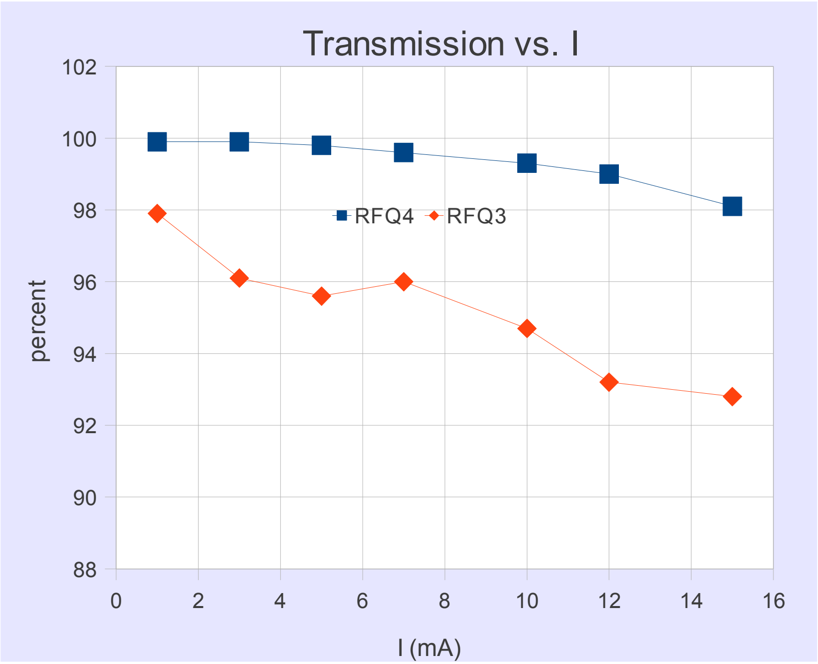


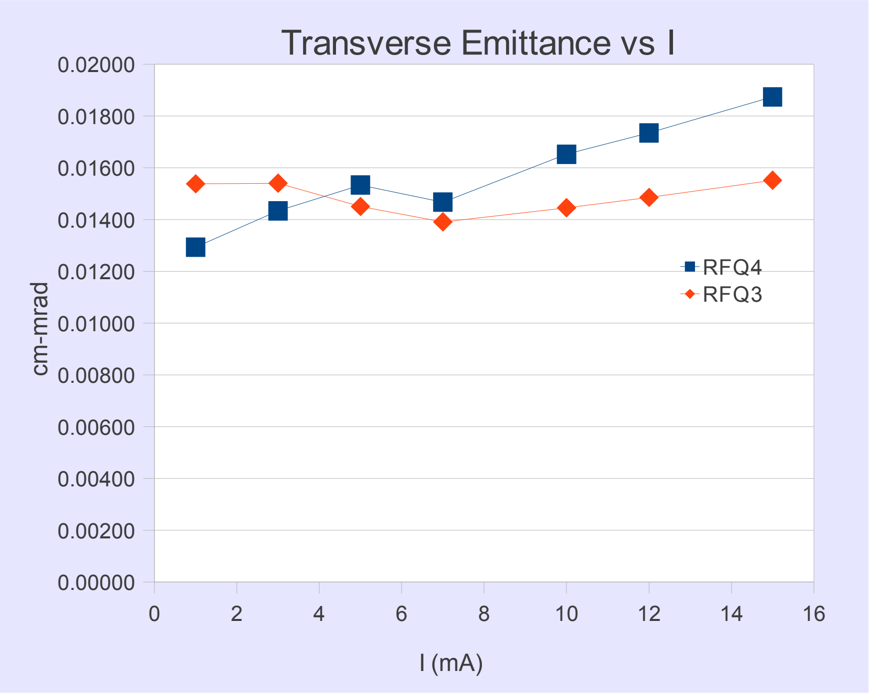
Current Dependence

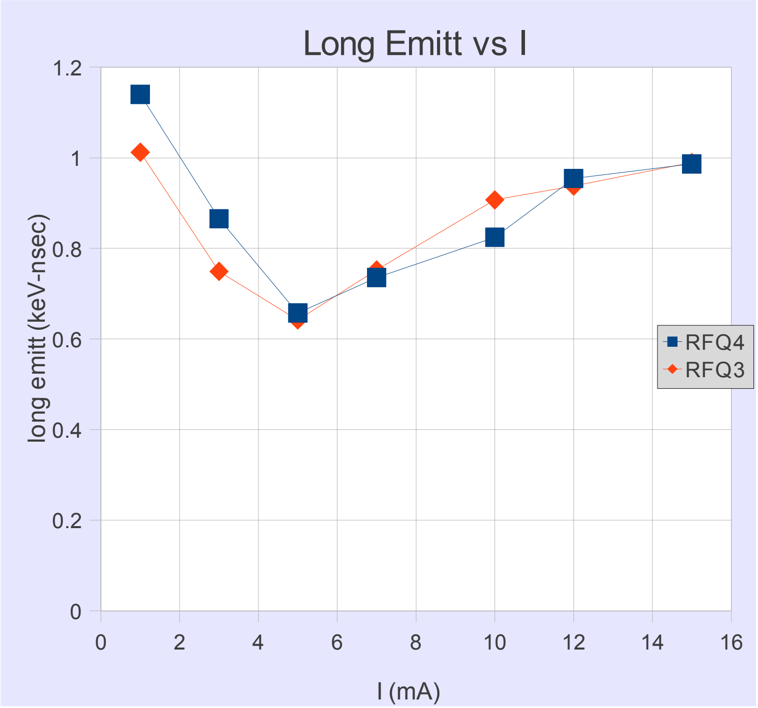
Compare present design (RFQ4) to previous design (RFQ3).

Slightly higher transverse emittance due to higher transmission (99.7 vs 95%)

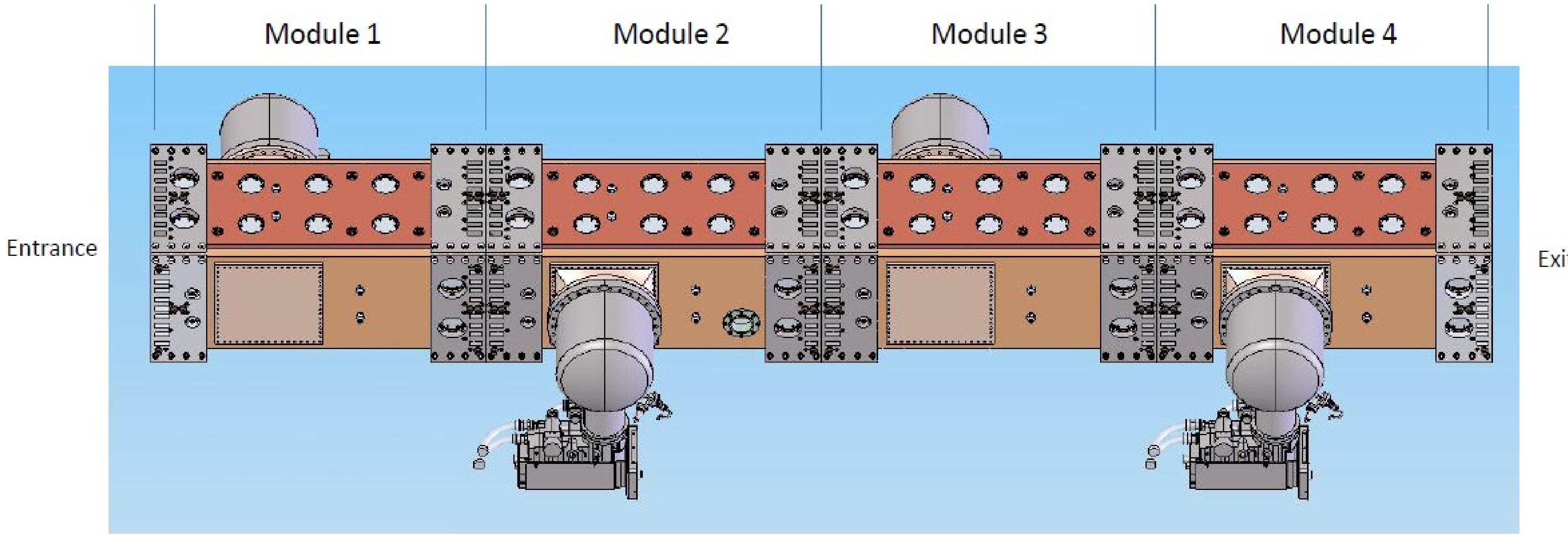
Optimized for 5 mA, but working range extends to at least 15 mA.







Mechanical Design Concept



Four modules, connected by “jackets” surrounding each module end

Special end terminations, cutback sections

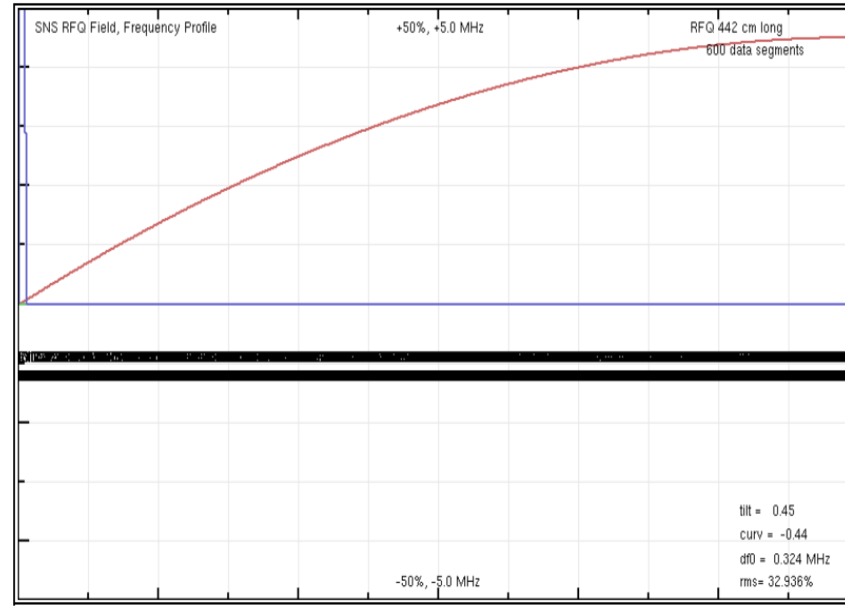
80 tuners, 32 (16 pairs, 4 pairs/module) pi-mode stabilizers, 48 sensing loops

Gun-drilled cooling passages: differential temperature frequency control

Perturbations to Field Flatness: Tuning

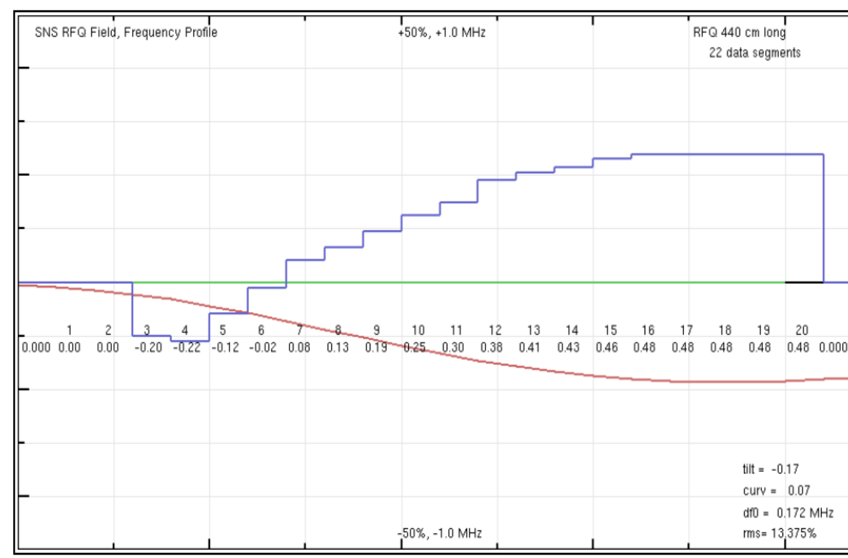
Entrance 6-cell radial matcher

Frequency perturbation of +0.33 MHz causes an uncorrected field tilt of +45% at the exit. Corrected by modifying the entrance end cutbacks in the vanes



Effect of the modulations of the vane tips

Local frequency variation -0.2 to +0.5 MHz, or an overall perturbation of +0.17 MHz, causing a field tilt of -18% at the exit. Corrected by the local tuners.



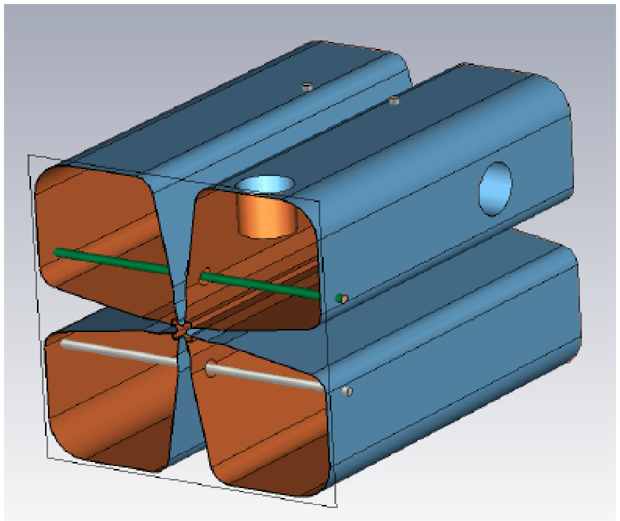
Group tuner sensitivity: +0.46 MHz/cm. Initial tuner insertion is 2 cm, or +0.92 MHz.

Pi-Mode Stabilizers: -4.5 MHz

“Bare” (Superfish) frequency about 3 MHz high

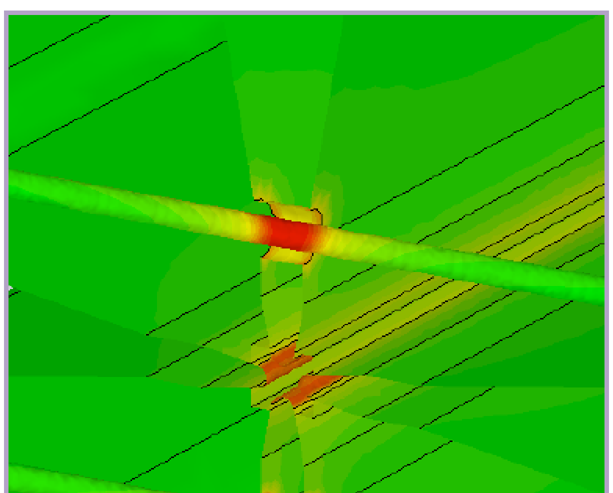
Pi-Mode Stabilizer and Tuner Simulations

Gennady Romanov doing 3-D MWS simulations on tuners, stabilizers and end cutbacks.

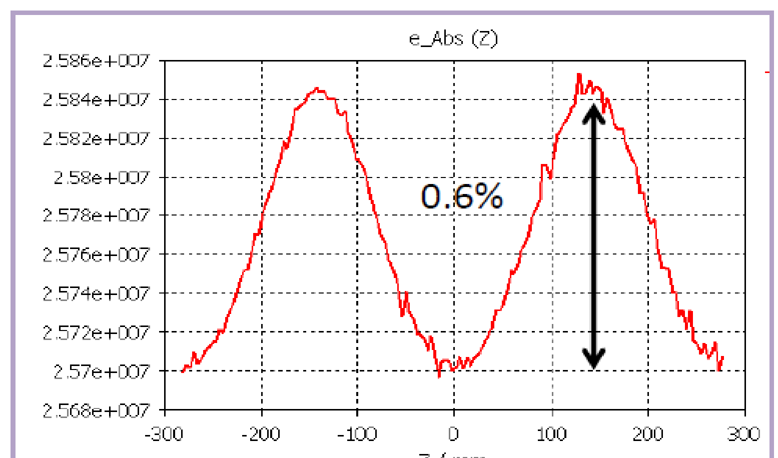


Period of RFQ with PISL

Period = 560 mm
PISL X(Y) = 52 mm
PISL rode radius 5 mm
PISL hole radius 10 mm
Distance between PISLs = 280 mm
Transverse size H = 167.35 mm
Q = 14640
F_quad = 162.55 MHz
F_dipole = 183.57 MHz
E_max_surface on the PISL = 15 MV/m
Field modulation = 0.6%



Surface electric field



E_abs in the gap (X=Y=5 mm) vs Z

LEBT and LEBT Chopper

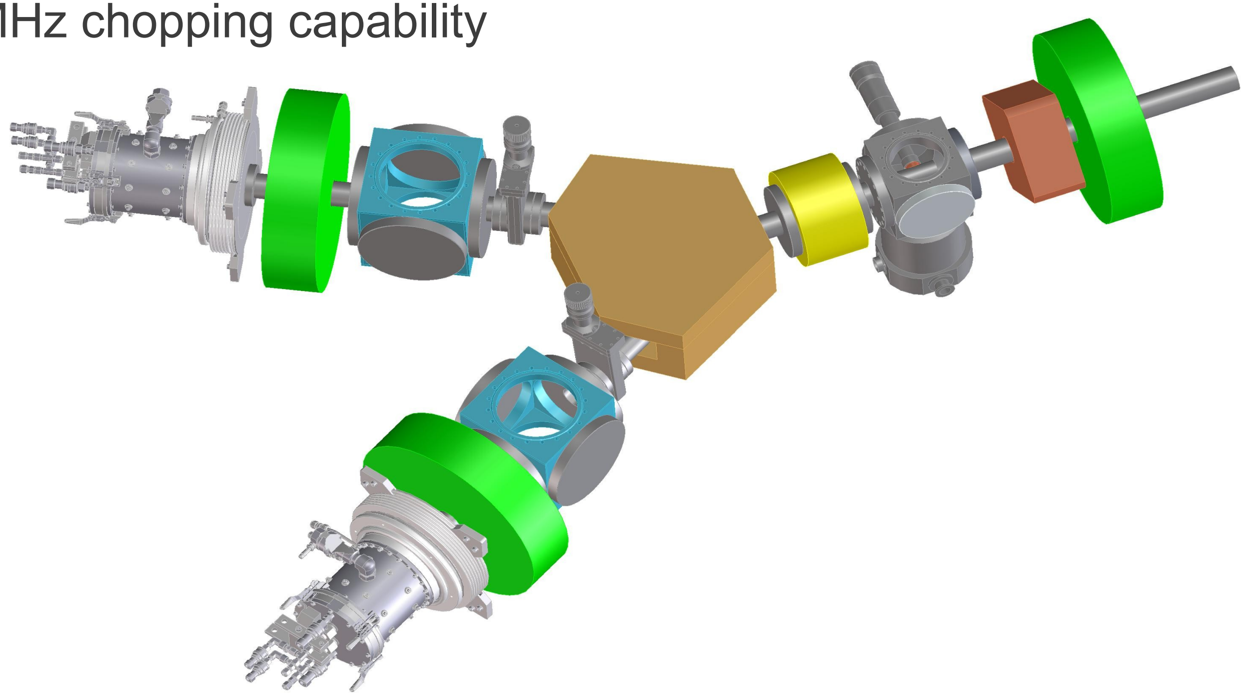
Requirements

Transport a nominal 5 mA H-minus beam from source to RFQ entrance

Provide 2 sources, selectable by a “slow” 20 degree magnet

Match the beam into the RFQ with a solenoid lens

Provide a 1 MHz chopping capability



LEBT Configuration

30 keV

5 mA DC beam

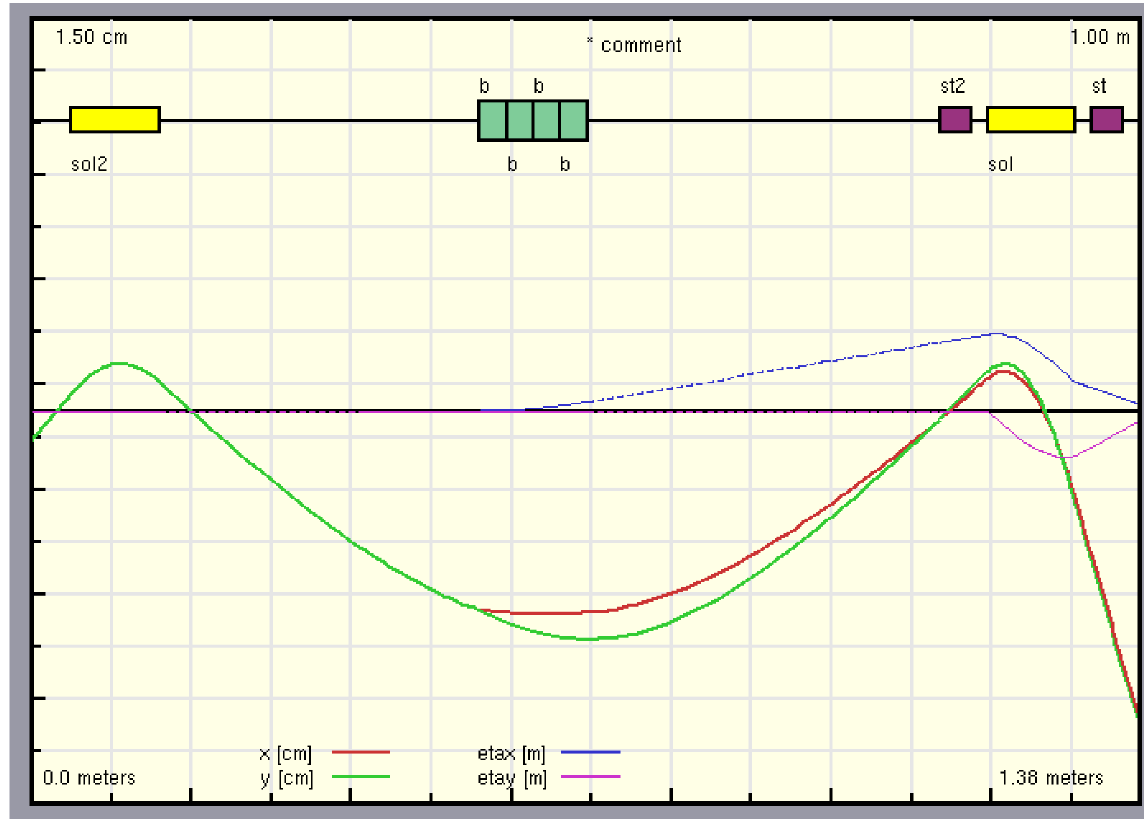
>90% neutralization

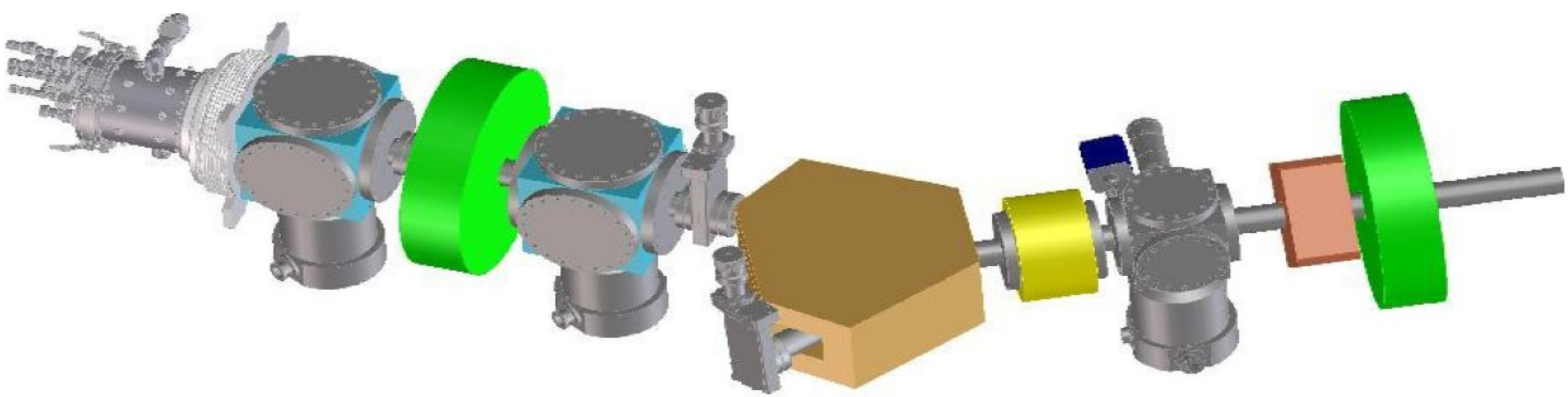
2 solenoids

2 ion H-minus ion sources

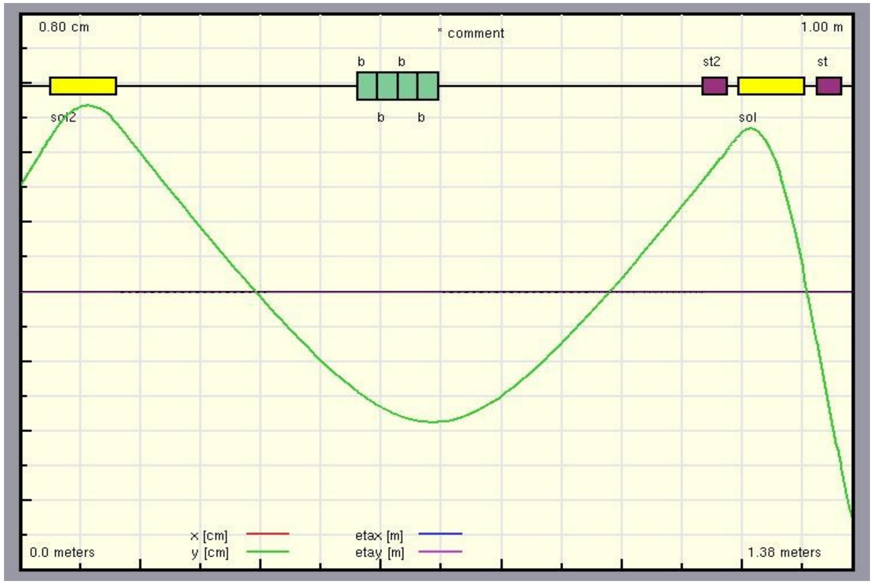
±20 degree selector magnet
chopper at end

1 MHz Chopper at end

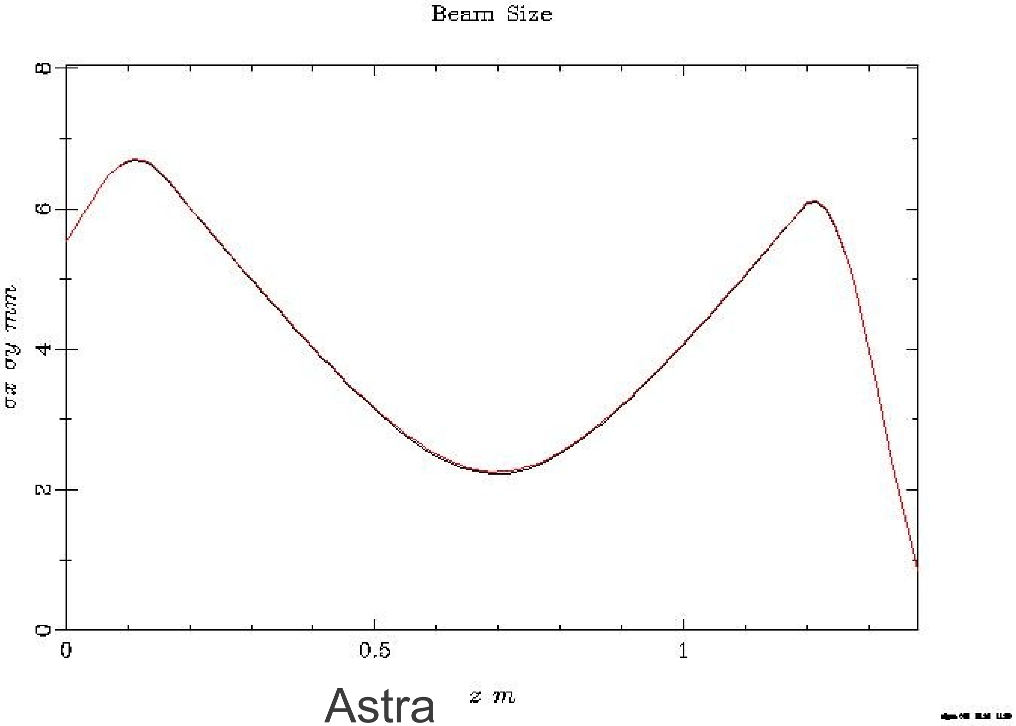




Astra macroparticle simulation of LEBT



TLAT



Astra

TLAT is based on a TRACE3D physics model. It is an envelope code that incorporates both 2-D and 3-D space charge, deflectors, steering, etc.

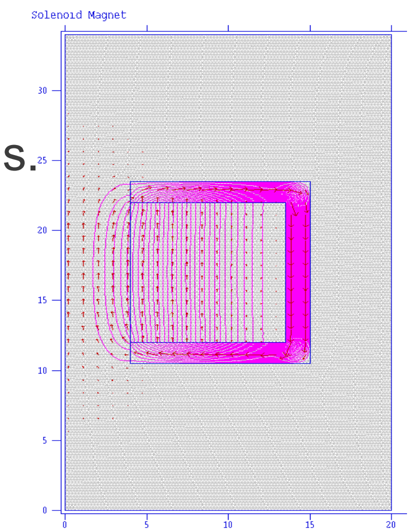
Astra is a workhorse of the electron community. It is a macroparticle code with 3-D PIC space charge. It works as well with hadrons and offers extensive graphics and analysis facilities. Accept ion source emittance scan and simulate nonlinear effects.

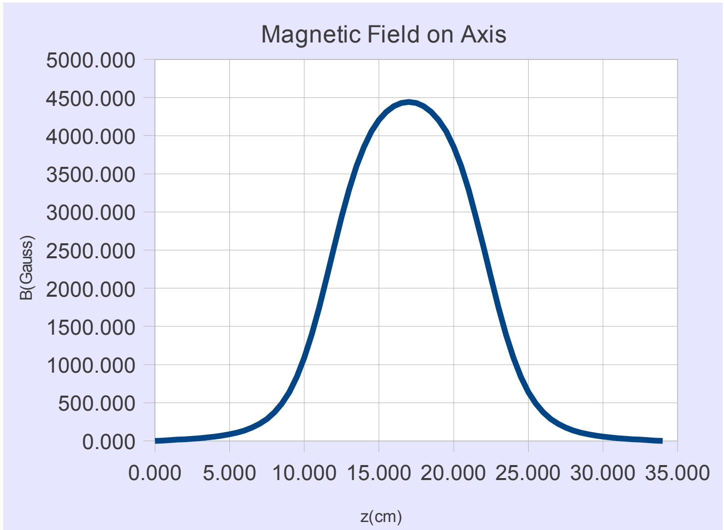
TLAT, Astra, Warp and Trace-3D all in agreement, provide different simulation approaches.

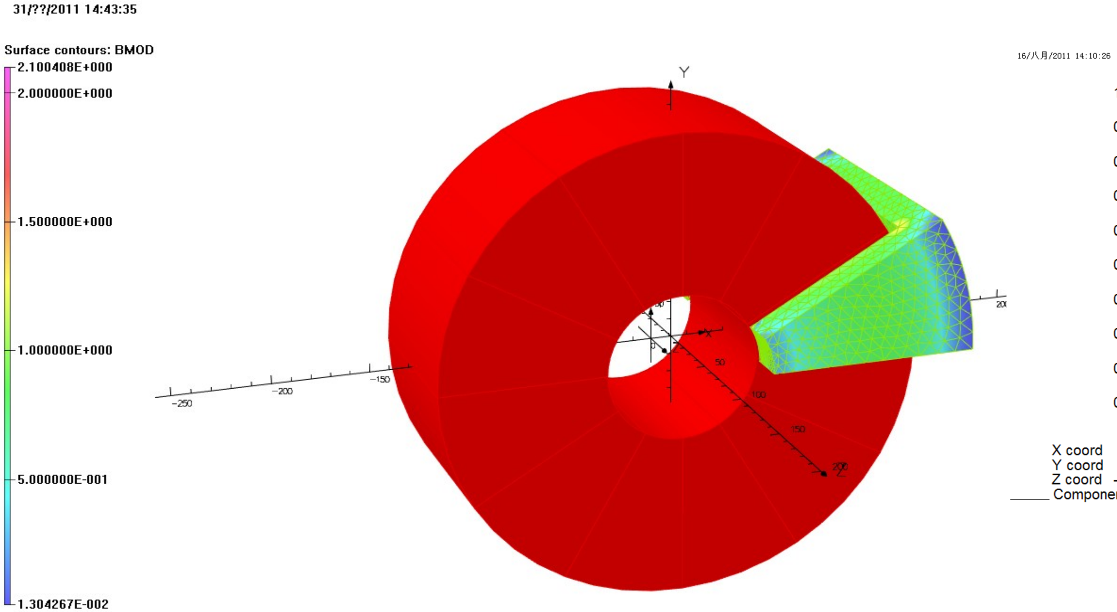
LEBT Solenoid Design

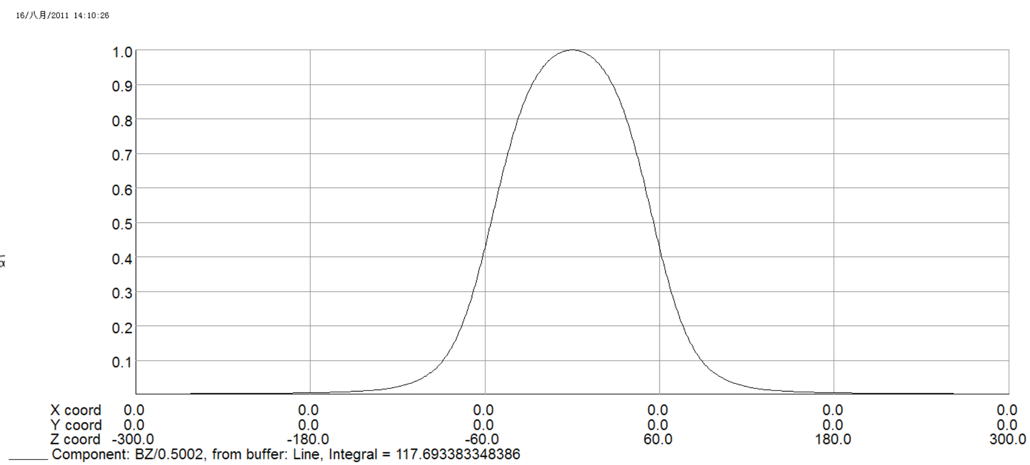
The 0.5 T, 11 cm solenoid initial LBNL design has been duplicated by IMP and is ready for engineering drawings.

The 20 degree bend magnet is next to be designed.









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Opera

Preferred LEBT Chopper Configuration

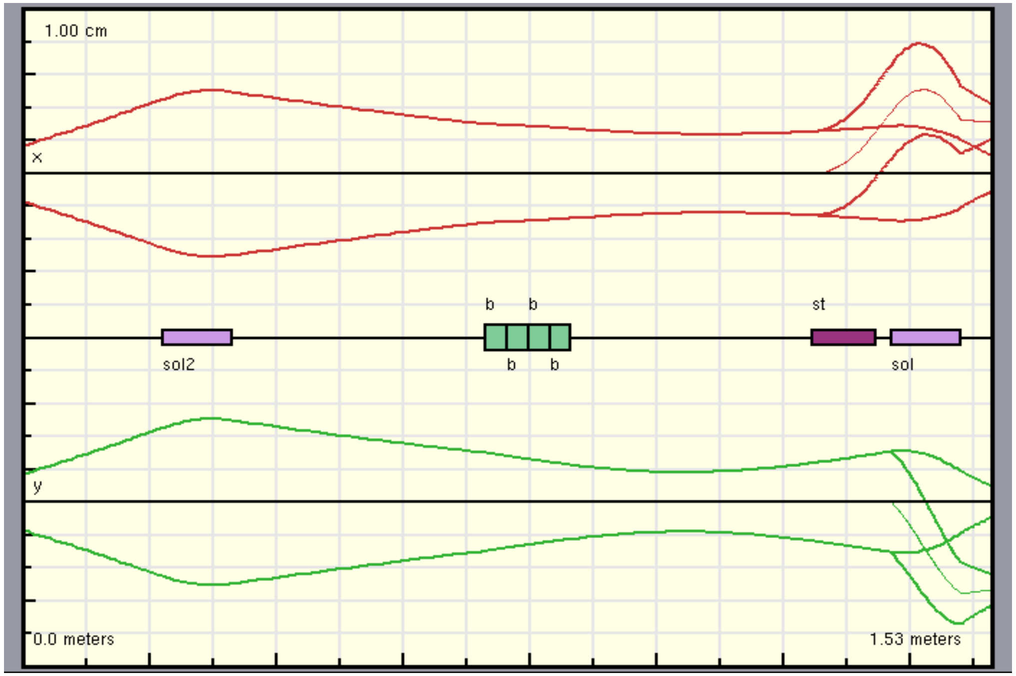
The current scenario includes placing a transverse electric-field chopper in front of the last solenoid in the LEBT. The deflected beam will be displaced and Larmor rotated in the solenoid and enter the RFQ off-axis in both displacement and angle in both phase planes.

The current chopper scenario calls for plates 3.1 cm apart and 10 cm long, driven in opposite polarities by high-voltage FET switches from static DC power supplies. The spacing corresponds to a stay-clear of 5.5σ of the rms beam size in the chopper.

In a practical configuration, a field of up to 48 kV/m can be generated between the deflecting plates.

The figure shows the beam trajectory through the LEBT with the chopper off and on. The chopper (red) precedes the final solenoid (purple).

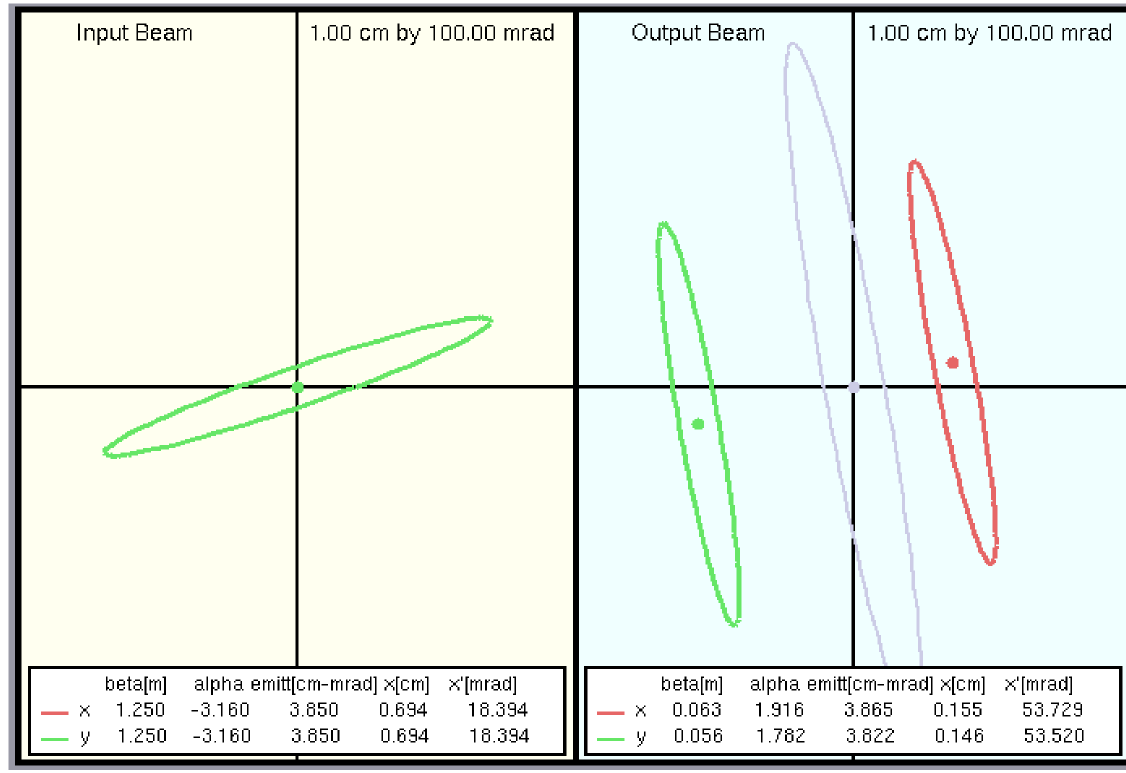
A beam ensemble of 25,000 particles constructed from measured emittance data from the ion source is transported through the LEBT, deflected by the chopper at various fields, and then transported through the RFQ.

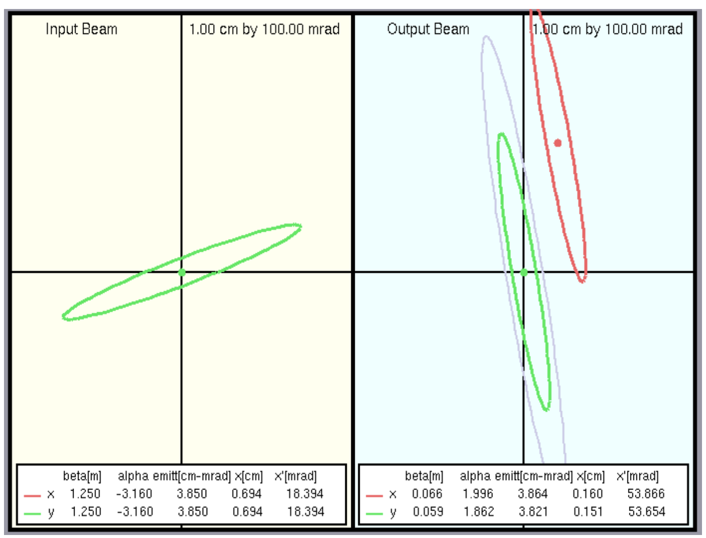


LEBT Chopper displacement of x and y phase spaces at RFQ Entrance

Chopping ahead of last solenoid in x-direction displaces both x and y ellipses.

Gray ellipse is RFQ acceptance ellipse orientation.



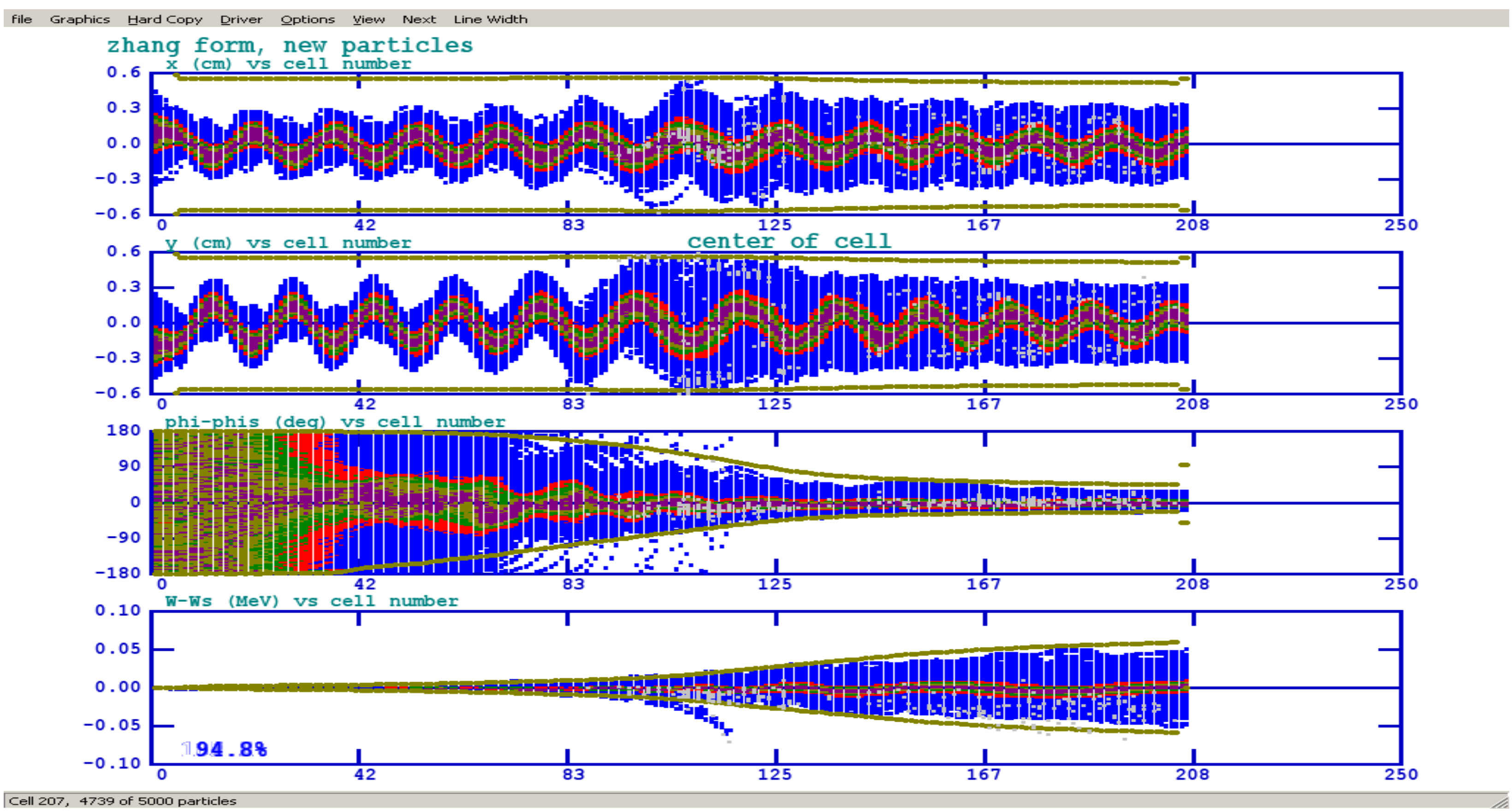


Phase space for post-solenoid chop.

RFQ transmission and output beam characteristics simulated with various chopper deflection field strengths to determine RFQ transmission and effect on RFQ output beam.

The RFQ Response to the LEBT Chopped Beam

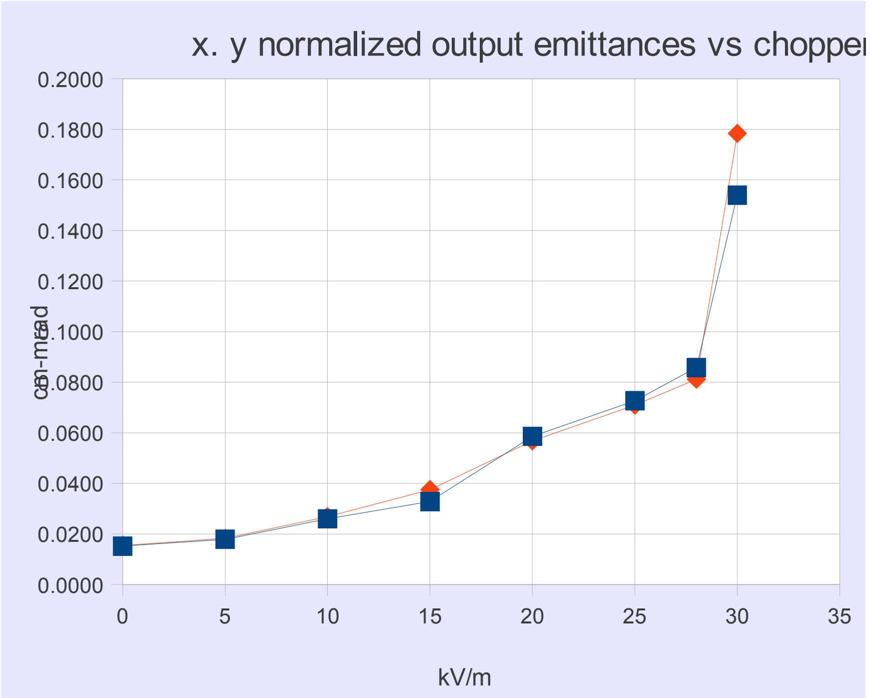
The chopped LEBT beam enters the RFQ and exhibits approximately 12 betatron oscillations about the central orbit. In addition, the off-center beam emittance is significantly increased by a factor of 2-3. The beam emerges from the RFQ off-axis and off-angle. This beam, during the LEBT chopper transition is to be removed by a fast chopper in the MEBT. The figure shows the beam trajectory with 10 kV/m field on the LEBT chopper and 95% transmission through the RFQ. The non-chopped transmission is 99.7%.

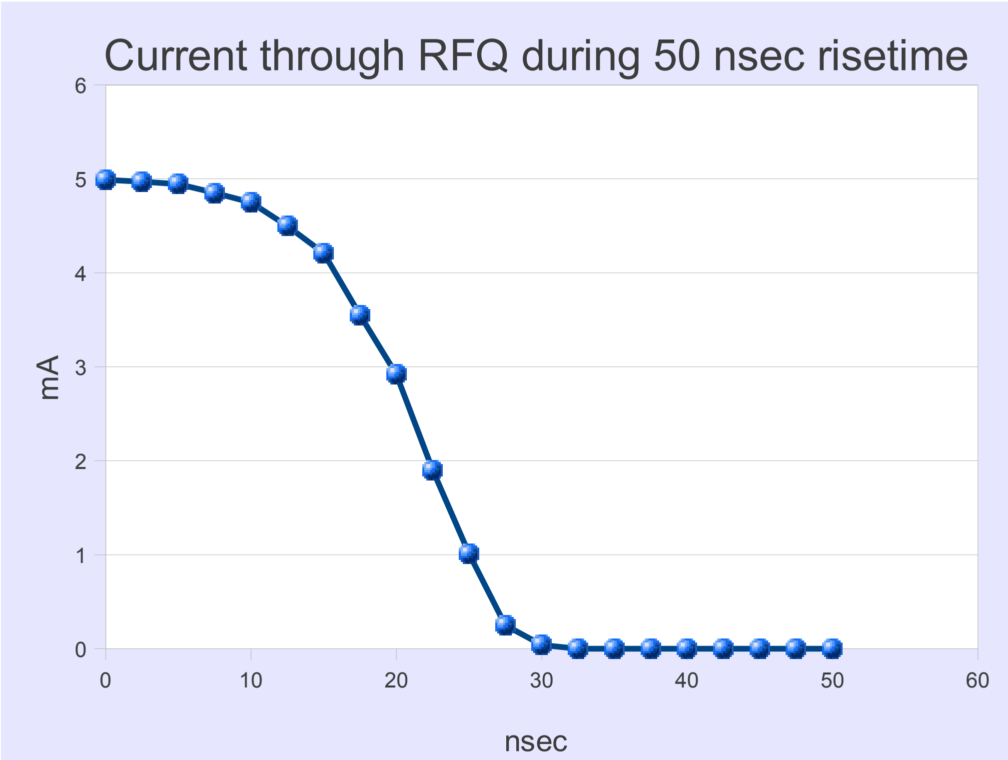


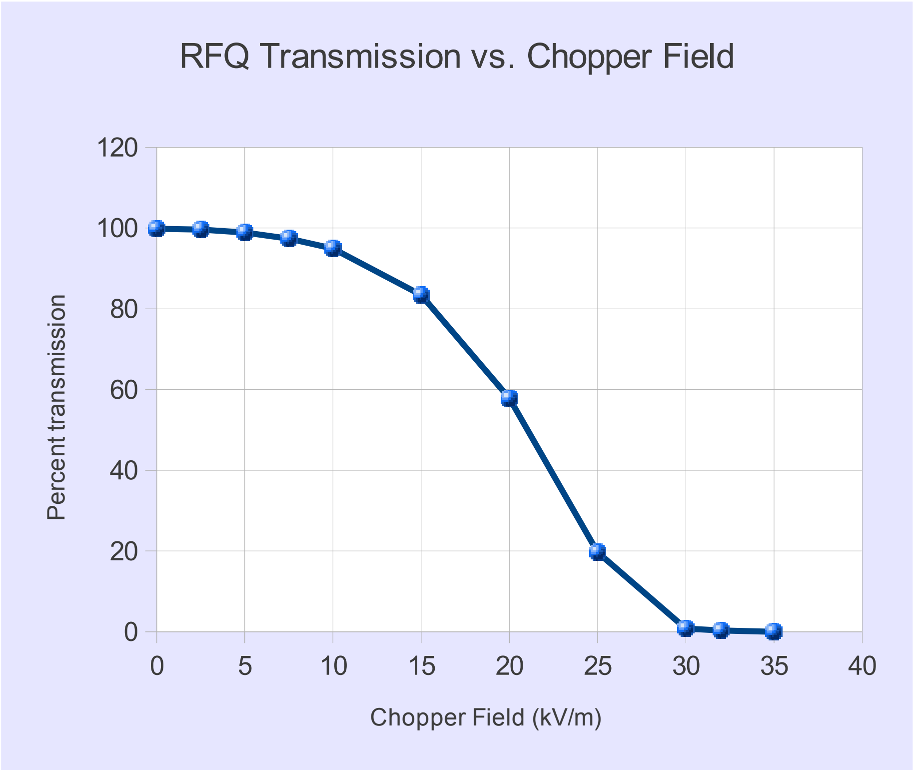
Effect of Chopping of RFQ Output

Rise/fall time during chop is about 25 nsec. During this time, the output emittance and beam trajectory will be out of specification.

The beam during this interval must be removed in the MEBT. The power in this beam







Challenges of LEBT Chopping

Off-axis beam at RFQ entrance is reproduced as off-axis beam at RFQ exit

Beam aperture at RFQ entrance is not effective in removing off-axis beam

Don't make the RFQ act as a beam collimator by using a very small aperture

Off-axis RFQ input beam must be cleaned up in the MEBT

For 500 microsecond, 10 Hz chop: remove "bad" edges in MEBT

For possible ca. 1 MHz LEBT chop: MEBT chopper should still apply

Faster LEBT chop: most beam will be off-axis and/or satellite bunches:
just use MEBT chopping

LBNL LEBT chopper: two scenarios:
before solenoid more effective and should be tested
after solenoid but with higher deflection voltage

The H-minus neutralizing plasma includes both positive ions and electrons, due to different production and loss rates, and they have different mobilities. Chopping should be as close to the RFQ as possible. Upstream LEBT transport is neutralized.

MEBT Chopper to Clean UP LEBT Chopper Beam

The 0.11 nC charge of unwanted beam will emerge from the RFQ during each transition of the LEBT chopper. The MEBT chopper must remove this part of the beam.

For a maximum LEBT chopper frequency of 1 MHz, 2×10^6 transitions occur each second, for an average current of 0.22 mA of chopper transition beam that must be disposed of on the MEBT chopper target. At a beam energy of 2.1 MeV, the power to be dissipated is 460 watts.

Some of this beam may be removed by stationary collimators in the MEBT, but the rest must be removed actively with the MEBT chopper synchronized to the LEBT chopper timing.

Maximum Chopping Frequency

The maximum LEBT chopping frequency will be limited to the 1 MHz range.

The beam velocity β = 0.008 is a very low velocity for traveling-wave deflectors, therefore, a simple parallel-plate chopper configuration is adopted. The transit time through plates 10 cm long is 42 nsec. Significantly shorter plates required a much higher voltage, difficult to switch at greater than a 1 MHz rate.

The DEI PVX-4150 pulser, included in this example, is rated at less than 25 nsec switching time of up to 1.5 kV. However, the switching rate is limited by the stored charge in the solid-state devices in the unit, which contribute the largest load capacitance. The cables to the chopper plates and the chopper itself contribute a small added load capacitance.

Power dissipation limitations in the DEI pulser limit the power $P = CFV^2$ to 150 watts, where the internal capacitance C = 200 pf, plus a small additional amount for cables and chopper plates, V is the switched voltage, and F is the switching frequency.

A practical solution is to limit the voltage to 750 volts and the frequency to 1 MHz to stay safely within the 150 watt power dissipation limit of the solid-state switches. A total voltage of 1.5 kV across the 3.1 cm chopper gap produced by +750 and -750 switchers produces a deflecting field to 48 kV/m, or about a 60% overvoltage on the LEBT chopper, reducing the beam switching time and increasing the extinction ratio.

LEBT Chopper Implementation

The transport through most of the LEBT requires the beam to be >90% space-charge neutralized: greater than 98% is expected. The neutralization will be lost after the chopper and through the final solenoid due to the motion of the beam centroid.

Simulations show that chopping at positions further upstream in the LEBT require impractical beam pipe dimensions and solenoid aperture and field.

An electron trap in the form of a biased aperture will precede the LEBT chopper to ensure upstream neutralization.

Simulations show that with neutralized transport up to the chopper, and completely unneutralized transport of 5 mA from the chopper through the final solenoid to the RFQ requires the last solenoid field to be raised by 24% to re-estabilish the proper matching conditions at the RFQ entrance, compared to a fully neutralized LEBT transport. The solenoid aperture remains the same as for the fully neutralized transport simulation.

The final configuration of the LEBT chopper will depend on measurements of the configuration to verify acceptable transport of unneutralized beam through the last segment of the LEBT without emittance degradation. The time dependence of partial neutralization in the segment following the chopper may contribute to emittance growth and will be experimentally measured and remediated if necessary by a clearing field.

LEBT R&D Program

The LEBT to be developed and tested incrementally

Extraction and 30 keV acceleration from the ion source
Electron diversion and trapping
Ion source emittance measurements
Chopper implementation at RFQ entrance
Establish matching parameters required by RFQ
Emittance, neutralization time measurements of chopped beam

Time-dependent simulations with WARP and Vorpal of LEBT chopper. LBNL has strong computational experience in this area.

The separation of the 30 keV acceleration, the magnetic transport, and the pulsed electric field chopper will ensure high reliability.

Post-Summary

The RFQ physics design for PXIE is complete

The RFQ mechanical design concept is complete

LBNL has started on the engineering drawings for both the PXIE and IMP RFQs

The D-Pace ion source is operating at LBNL

Emittance measurements repeated at LBNL: compare well to TRIUMF

LEBT beam dynamics solution established

Mechanical design concept under way

Detailed engineering not yet started